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Validation of PV-RPM Code in the System Advisor Model

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Validation of the PV-Reliability Performance Model in the System Advisor Model

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Abstract

This paper describes efforts made by Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) to validate the SNL developed PV Reliability Performance Model (PV-RPM) algorithm as implemented in the NREL System Advisor Model (SAM). The PV-RPM model is a library of functions that estimates component failure and repair in a photovoltaic system over a desired simulation period. The failure and repair distributions in this paper are probabilistic representations of component failure and repair based on data collected by SNL for a PV power plant operating in Arizona. The validation effort focuses on whether the failure and repair distributions used in the SAM implementation result in estimated failures that match the expected failures developed in the proof-of-concept implementation. Results indicate that the SAM implementation of PV-RPM provides the same results as the proof-of-concept implementation, indicating the algorithms were reproduced successfully.

ACKNOWLEDGMENTS

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NOMENCLATURE

AC	alternating current
CI	confidence interval
DC	direct current
DOE	Department of Energy
DNI	direct normal irradiance
DHI	direct horizontal irradiance
HV	high voltage
kWh	kilowatt-hour
LV	low voltage
MW	megawatt
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PV	photovoltaic
PV-RPM	PV-Reliability Performance Model
SAM	System Advisor Model
SNL	Sandia National Laboratories
TMY	Typical Meteorological Year
W	Watt

1. INTRODUCTION

1.1. Purpose

This paper describes efforts made to validate the PV-Reliability Performance Model (RPM) code with failure distributions developed from operations and maintenance (O&M) records at the 3.5 MW_{DC} crystalline silicon section of the Springerville PV plant, located in eastern Arizona. The PV-RPM code enhances the standard PV performance model, where probabilistic events are injected into the system to simulate how faults, failures and repair actions can impact PV performance, operational costs and ultimately energy output. The effort described in this paper is narrowly focused on validating the model in terms of the number of fault/failure events with supporting discussion on the resulting impact of different events on modeled energy performance. Comparing actual events from the PV plant to proof-of-concept expected model outputs previously developed by SNL alongside the results in the new SAM implementation will reveal if the component events can be accurately modeled considering that inputs are probabilistic, which necessitates presenting results as a range of values and not a "single" value. Internal validation of hypothetical PV systems (not described in this paper) by NREL and Sandia on different elements of the code was completed in 2016 to ensure that this new feature did not impact the SAM source code, and that different event distributions performed similarly between the proof-of-concept version and the new SAM version.

1.2. Background

The proof-of-concept version of PV-RPM was developed in 2010 by Miller et al. (2012a, 2012b) and also presented in an unpublished user manual (Miller, 2013) which describes how to conduct reliability analysis within a PV performance modeling framework, and presents a method for optimizing different O&M strategies with multiple hypothetical plant configurations. At the same time PV-RPM was being developed, an effort by SNL to gather O&M records at the Springerville, Arizona PV plant was underway to develop probabilistic distributions for use within the PV-RPM model. A paper by Moore and Post (2007) provides some background on the operations of the plant during the time period that SNL had access. Also, see Section 1.3 for more discussion. These distributions were then checked against a reliability block diagram model and early versions of PV-RPM to see what degree the reliability model matched the actual and expected failures at the plant.

These efforts, however did not extend to making the algorithms widely available to the PV modeling community, with only a feature-limited player version available for download and use. SNL and NREL have successfully transferred the existing proof-of-concept PV-RPM algorithm to the System Advisor Model (SAM) LK scripting language to make it more accessible and transparent. The previous analysis and data as described by Collins et al. (2009), and Collins et al. (2010) is used here to validate the new implementation in SAM to ensure that the reliability functionality works as intended, and simulated results in SAM (presented as a mean with confidence intervals) can approximate expected events from the proof-of-concept version of PV-RPM. Figure 1 presents the different models and platforms for reliability implementation.

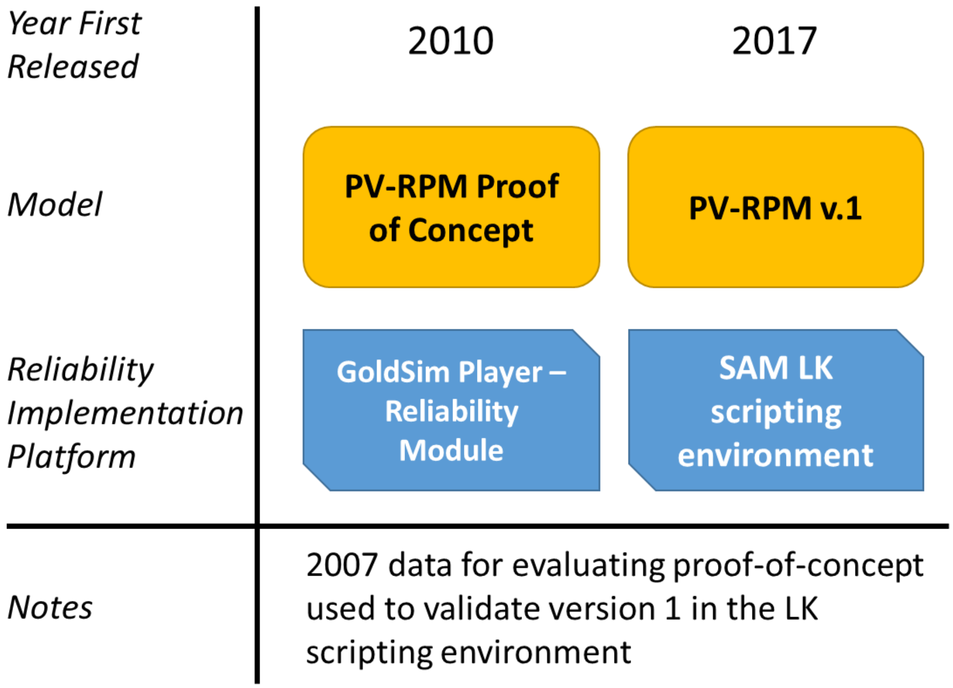

Figure 1. Timeline of Model and Reliability Implementation Platform Development

1.3. Past Validation

Early efforts by Collins et al. (2009) presented expected failure results compared to actual results over a 5-year time period. Expected 10- and 20-year failures were also presented as a projection based on model output. The results did not address stochastic uncertainty in terms of displaying the mean, median and any level of confidence intervals, nor was there a discussion on set-up parameters for the Monte Carlo analysis. Despite these deficiencies, the expected failure results will be used in this validation (See Table 2 below).

A sensitivity study by Collins et al. (2010) and Mundt et al. (2011) outlined different validation efforts aimed at weather variability, system failure characteristics, inverter performance, module performance and system design. The resulting analysis used Flagstaff for the TMY station, which is 170 miles away from the PV plant, compared to Show Low Municipal TMY, which is only 40 miles away with a more similar climate. These results were useful for development of the proof-of-concept model, however will not be used in the validation presented in this paper for the following reasons: 1) The sensitivity analysis was conducted on only one inverter power block out of 26, 2) The previous research introduced a large amount of uncertainty into the energy production estimates using a TMY location that is not representative of the site, and 3) the sensitivity study was not focused on comparing actual failures with estimated failures.

2. METHODOLOGY

2.1. Model Setup

The PV-RPM code implemented in SAM was analyzed by NREL to ensure compatibility with the SAM source code. This included the addition of new features not currently tracked in SAM, including DC combiner boxes and transformers, to ensure the parallel and series components can be modeled as a whole and not fractions of a component. Currently, SAM has the ability to model four sub-arrays, however the PV-RPM code only allows for the PV system to be modeled as one array. This is consistent with how the proof-of-concept was set up. This meant a few decisions had to be made on how to handle the fact that in the Springerville system, there were both even and odd combinations of inverters connected to the step-up transformer that were not able to be modeled exactly the same as in SAM. Future versions of PV-RPM could eventually model more complex systems if both larger numbers of subarrays are available in the PV-RPM implementation in SAM and if SAM was able to model irregularly set-up systems.

PV system details are provided below in Table 1. Some of this data was gathered from Moore and Post (2007), Collins et al. (2009), and unpublished reports and data files at SNL. Other inputs, such as the TMY station, are based on a best estimate for weather conditions at the site.

Table 1. PV System Input Parameters for Springerville, AZ Power Plant

	SAM PV-RPM Model	Estimated Actual
SAM Version	Beta 2016.7.21	N/A
Weather Location	Show Low Municipal TMY3	N/A[i]
Number of Modules	11700	11700
Modules per string	9	9
Strings in Parallel	1300	1300
Number of Inverters	26	26
Number of Combiners	650	650
Number of LV Transformers	26	26
Number of HV Transformers	2[ii]	Assumed to be 7
DC Nameplate	3493 kW	3500 kW
Array Tilt	34 degrees	34 degrees
Array Azimuth	180 degrees	180 degrees
Sky Diffuse	Perez	N/A
Irradiance Data	DNI and DHI	N/A
Mounting	Glass/Cell/Polymer Open Rack	Fixed tilt rack
Module	Schott ASE 300 DGF-50 (300) 2007E	Schott ASE 300 DGF-50
Inverter	Xantrex PV100S-208 208V	Xantrex PV-150[iii]
Module Degradation	0.5%/yr	Unknown

i – The proof-of-concept model used TMY 2 Flagstaff, however this table is only comparing what was assumed to be at the site to the inputs used in the SAM Implementation of the PV-RPM model, and not the proof-of-concept model validation as inputs to that model are not available. Only output as presented in Table 2 is available. SNL does not have access to actual weather data at the site.
ii – There are four inverters connected to one step-up HV 480V/34.5kV transformer. Twenty-six inverters are connected to seven transformers. Either the last transformer has only two inverters, or the last two transformers have three inverters. Because of the

uneven number of HV transformers (seven) we could only model two HV transformers instead of seven as the number of inverters per transformer need to be even in the SAM LK script.
iii – Information on the site from different reports state that the inverter type is a Xantrex PV-150. An exhaustive search of inverter datasheets only found a PV-100 in performance model databases and from archived on-line repositories. It's not clear if this was a non-commercial inverter used just for this site, the authors of the papers had the incorrect inverter name, or it has rated capacity of actually 100 kW despite the name having "150". The SAM inverter database does not have a 150 kW 208V model, and therefore a 100 kW model was used. When modeling with a 100 kW inverter, the DC to AC ratio is 1.33. Use of the 100 kW inverter may result in more 'clipping' in the model than if a 150 kW rated inverter was used.

Most of the inputs above were inputs into the main SAM user interface, with the exception of "Number of Combiners" and "Number of Transformers," which were entered into the SAM LK reliability script.

The seven "components" in the SAM LK implementation that can fail and be repaired are listed below, from downstream at the energy production end, to collection, inversion and ultimately delivery to the utility.

- Module failure
- String failure
- DC Combiner failure
- Inverter Failure
- Transformer Failure
- AC Disconnect Failure
- Tracker Failure
- Grid Failure*

* A Grid Failure is not a component, but can be modeled to represent an event that can impact the ability of the PV system to export energy due to circumstances where the grid is offline due to a fault on the grid side, or on the PV side which prevents the PV system from exporting energy.

The failure and repair distributions used in this analysis are presented below in Table 2 and were collected from Collins et al. (2009) as well as other internal unpublished papers by SNL. Added to this table are the actual and expected (modeled) failures from the initial analysis for a 5-year timeframe (2003-2007) and the expected 10- and 20-year failures for the specific components, also from Collins et al. (2009). The 26 "arrays" were on-line at different times as shown in Moore and Post (2007), however they were modeled having the same operational start date. SNL does not have access to event data past the first 7 years, therefore any comparisons between models to the 10- and 20-year expected failures cannot be validated against actual failures.

Table 2. Failure and Repair Distributions – Including Actual and Expected Failures from Collins et al. (2009)

Component	Distribution Type	Param. 1 (shape or mean)	Param. 2 (scale or stdev)	5-yr actual failure	5-yr expected failure	10-yr expected failure	20-yr expected failure
Module Failure	Weibull	0.28	5.0E+12	29	26	31	38
Module Repair	Lognormal-n	-1.37	13.11	N/A	N/A	N/A	N/A
DC Combiner Failure	Weibull	0.51	1.2E+06	34	25	35	50
DC Combiner Repair	Lognormal-n	-0.98	2.07	N/A	N/A	N/A	N/A
Inverter Failure	Exponential	0.00022	N/A	16	10	20	41

Lightning							
Inverter Repair Lightning	Weibull	0.73	10.8	N/A	N/A	N/A	N/A
Inverter Failure Catastrophic	Exponential	0.00278	N/A	125	132	231	429
Inverter Repair Catastrophic	Lognormal-n	-4.25	2.27	N/A	N/A	N/A	N/A
HV Transformer Failure	Weibull	0.58	7100	5	4	5	9
HV Transformer Repair	Weibull	0.53	1.36	N/A	N/A	N/A	N/A
AC Disconnect Failure	Weibull	0.35	11000	22	17	23	31
AC Disconnect Repair	Weibull	0.71	1.4	N/A	N/A	N/A	N/A
Grid Failure	Lognormal-n	3.62	1.7	N/A	N/A	N/A	N/A
Grid Repair	Weibull	1.07	0.16	N/A	N/A	N/A	N/A

The reliability data from Table 2 is then input into the SAM LK code as shown below in Figure 2. Each failure mode is represented as a statistical distribution, and repairs (also represented as a statistical distribution) can be made, or the component can be left in a non-functional state for the remainder of the simulation. Costs and labor time associated with the repair action can also be added, though are not included for this exercise. For the purposes of this validation, detail into how to develop failure modes and distributions will not be discussed. It is important to note that the purpose of this validation is to compare "expected" failures from Collins et al. (2009) to the new simulated or "expected" failures in the SAM implementation to evaluate if the distributions were developed and sampled properly. This paper does *not* evaluate, nor attempt to change the original distributions developed and interpreted by Collins et al. (2009) with the TEP dataset. Therefore, we will not be comparing the SAM implementation of PV-RPM simulated failures to the "actual" failures shown in Tables 2-9, and 10. The actual failures are included to give the reader a sense of how well early researchers did in developing distributions that could approximate actual events with the 5-year dataset.

More detail will be presented in future manuscripts, conference papers and presentations, as well as help features within SAM to guide users how to set up their own fault/failure distributions with their PV system failure and repair data.

```
// Modules
global modules = alloc(num_modules);
global module_meta = null;
module_meta.can_fail = true;
module_meta.number = num_modules;
module_meta.warranty.has_warranty = true;
module_meta.warranty.days = 20 * 365; //years converted to days
//failure mode 1: normal failures
module_meta.failure[0].distribution = 'normal';
module_meta.failure[0].parameters = [4 * 365, 1 * 365]; //mean, std, years converted to days
module_meta.failure[0].times = null;
module_meta.failure[0].labor_time = 2; //hours
module_meta.failure[0].cost = 322; //$
//failure mode 2: defective failures
module_meta.failure[1].distribution = 'exponential';
module_meta.failure[1].parameters = [0.5 / 365]; //failures per year converted to days
module_meta.failure[1].times = null;
module_meta.failure[1].labor_time = 2; //hours
module_meta.failure[1].cost = 322; //$
module_meta.failure[1].fraction = 20 / 100; //% converted to fraction
module_meta.repair.can_repair = true;
module_meta.repair.distribution = 'lognormal-n';
module_meta.repair.parameters =  [60, 20]; //mean, std, in days
module_meta.repair.times = null;
module_meta.degradation.can_degrade = true;
module_meta.degradation.rate = 0.05; //%/year
```

Figure 2. LK Script Example for Setting Up Module Failure and Repair Distributions

Figure 2 shows an example of how module failure and repair modes are set up in the SAM LK scripting language. In this example, two failure modes are defined, with one repair distribution covering all failures. Multiple repair distributions can also be assigned, with one failure type receiving one repair type. This is important based on the fact some failures may require greater attention than others, such as inverter faults that can be reset remotely, or other inverter faults that require a site visit and may take longer to repair.

For this validation, only one failure mode per component is simulated. String failures are not simulated as distributions were not initially developed from the Springerville data. The ability to simulate string failures is available if there is data to support the analysis. Tracker failures are not simulated as this is a fixed-tilt system. Grid failure distributions were developed from earlier analysis, however there was no summary of how many grid events actually occurred to make a comparison. The following sections will discuss reliability simulations made with failures and repairs to modules, dc combiners, inverters, ac disconnects and transformers.

2.2. Evaluating Events with Single Components

The purpose of this test was to ensure that the actual failure in the field is modeled in the right location in the performance model. For example, any DC combiner failure would ensure no electricity is delivered from an operational string of modules to an inverter. This was done by making the component fail based on the distribution and comparing the relative impact to the power and energy output. Components further down on the DC side (modules, DC combiners) should have a different power and energy impact compared to inverter and transformer outages. We also evaluated failure only, and failure and repair results to validate the performance differences and cumulative impacts when failures are not addressed. E.g., fewer components can fail over time if they remain in a failed state, though may be able to fail more often in the same simulation if repaired.

Ten realizations were completed over a 5-year analysis period to evaluate against simulated failures from the proof-of-concept PV-RPM model as described by Collins et al. (2009) (5-year expected failure in Table 2). Ten- and 20-year expected failures from Collins et al. (2009) were also compared with results from the new SAM PV-RPM v.1 implementation. Actual 10- and 20-year failures are not available to review. As this section is intended to review behavior more than evaluating model accuracy against actual failures, only 10 realizations were run. Section 2.4 presents a more robust simulation with 100 realizations to understand how well the estimated failures from failure and repair distributions compare between the proof-of-concept and the SAM PV-RPM v.1 implementation.

2.2.1 Modules

Using the configuration outlined in Table 1, only modules were allowed to fail and/or be repaired. All other failure modes were turned off.

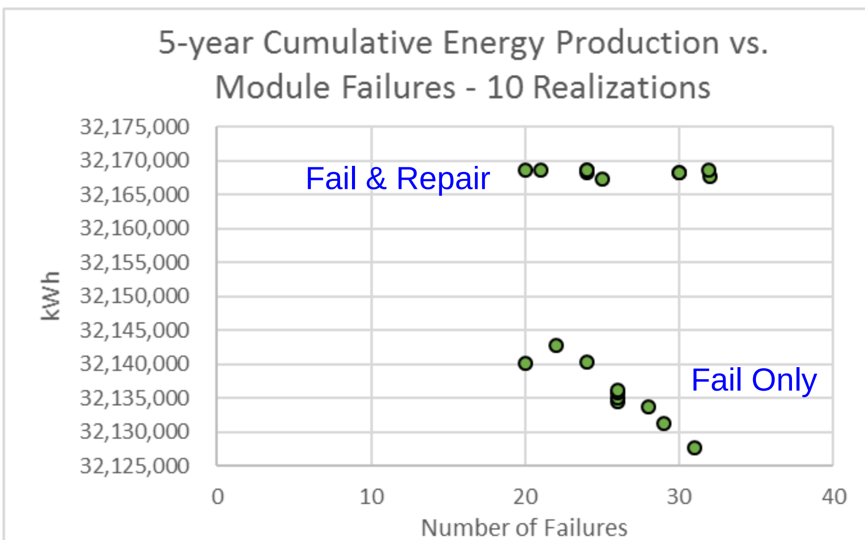

Figure 3. Simulated Module Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 3 that say "Fail Only" represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the "Fail Only" distributions is 25.8 failures and the "Fail & Repair" is 26.2 (Table 3). Since there are over 11,000 modules, the concept of fewer components failing if they remain in a failed state does not necessarily hold true with the distribution used in this simulation. If the model was allowed to run for 25 years, or failure rates increased, then the result may show a significant reduction in failures in the "Fail Only" scenario.

The spread in cumulative energy production values from the "Fail Only" group is due to the failed modules not being repaired with more energy lost than if the modules were repaired as shown in the group of 10 realizations at the top of the graph. The difference in "Fail Only" cumulative energy production realization results is ~15,000 kWh over 5 years, while the "Fail & Repair" scenario is ~1,300 kWh over 5 years. The results are as expected, considering greater energy production over multiple realizations when modules are able to be replaced.

Table 3. Module Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al., 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
29	26[i]	26.2	27.4	24.4

i - The 5-year expected is assumed to be the mean of multiple realizations, though Collins et al. (2009) does not specify the confidence intervals or number of realizations.

Table 3 presents results of actual module failures, compared to the proof-of-concept 5-year expected value by Collins et al. (2009) and the 5-year simulated mean value from PV-RPM in SAM. The PV-RPM SAM simulation reveals that 95% of the sampled intervals between 24.4 and 27.4 failures contain the true mean of 26.2 failures. The simulation assumes modules were replaced over the 5-year analysis period, as demonstrated by both failure and repair distributions in Table 2. The 5-year expected and 5-year simulated mean failures are ~26. The 5-year actual is 29 failures.

Even with only 10 realizations, the expected and simulated values match as they utilize the same failure and repair distributions from Table 2. This indicates that for module failures, the new SAM implementation of PV-RPM follows the proof-of-concept implementation.

2.2.2 DC Combiners

Using the configuration outlined in Table 1, only DC combiners were allowed to fail and/or be repaired. All other failure modes were turned off.

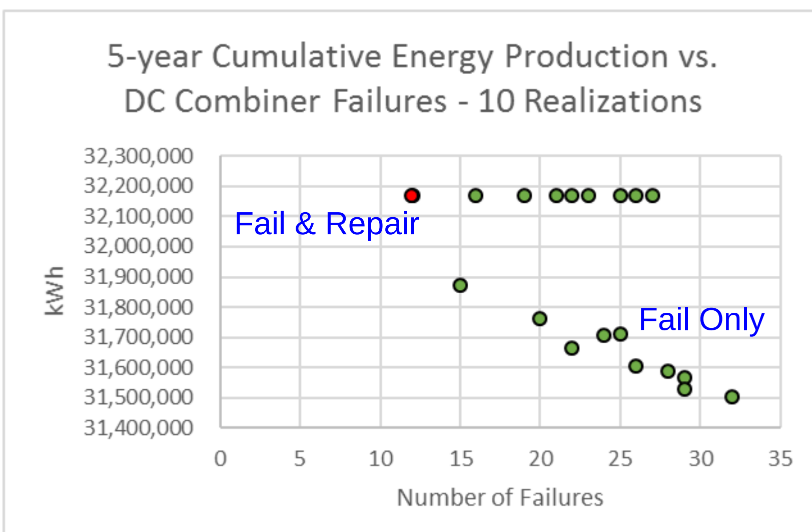

Figure 4. Simulated DC Combiner Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 4 that say "Fail Only" represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the "Fail Only" distributions is 25.0 failures and the "Fail & Repair" is 20.3 (Table 4). There are 650 DC combiners in this simulation and just like for modules, the concept of fewer components failing if they remain in a failed state does not necessarily hold true with the distribution used in this simulation. If the model was allowed to run for 25 years, or failure rates increased, then the result may show a significant reduction in failures in the "Fail Only" scenario.

The spread in cumulative energy production values from the "Fail Only" group is due to the failed DC combiners not being repaired with more energy lost than if the DC combiners were repaired as shown in the group of 10 realizations at the top of the graph. The difference in "Fail Only" cumulative energy production realization results is ~366,000 kWh over 5 years, while the "Fail & Repair" scenario is ~800 kWh over 5 years. The results are as expected, especially when compared to modules when moving closer to the inverter when one combiner outage can have a larger energy loss impact than one module outage.

This is a case where 5% of the sampled intervals did not contain the true mean value from the Collins et al. (2009) analysis, as the estimated mean of 20.3 within confidence interval of 16.4 to 24.2 was below the 5-year expected value of 25 failures (Table 4). It is possible that this was due to only using 10 realizations. More discussion on this is presented in Section 2.4, Table 11 which shows the results of failure events only (no energy loss estimates) for 100 realizations.

Table 4. DC Combiner Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al., 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
34	25[i]	20.3	24.2	16.4

i - The 5-year expected is assumed to be the mean of multiple realizations, though Collins et al. (2009) does not specify the confidence intervals or number of realizations.

2.2.3 Inverters

Using the configuration outlined in Table 1, only inverters were allowed to fail and/or be repaired. All other failure modes were turned off. Two different failure modes were evaluated. One from general failures and the other due to lightning. Both are presented below.

2.2.3.1 Lightning

Lightning impacts to inverters were modeled in SAM using data from Collins et al. (2009) as presented in Table 1.

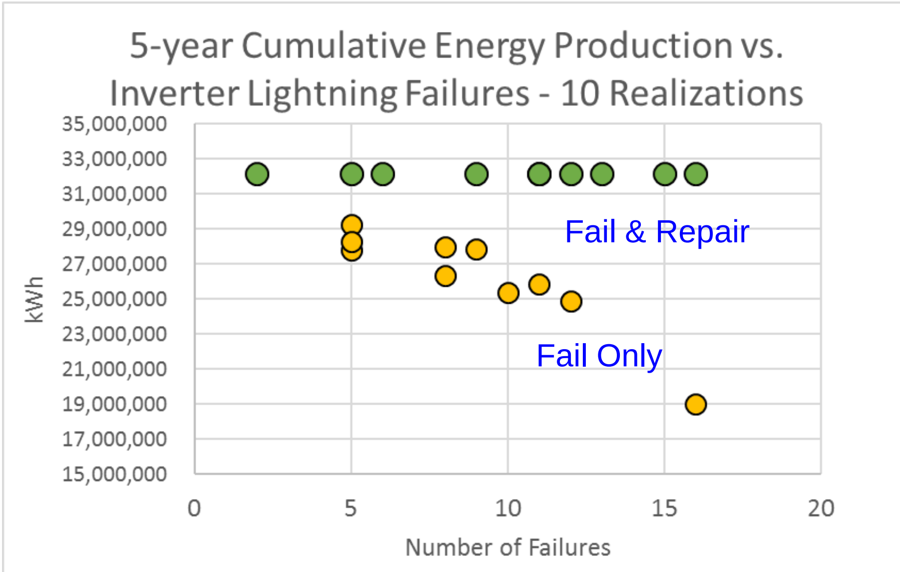

Figure 5. Simulated Inverter Lightning Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 5 that say "Fail Only" represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the "Fail Only" distributions is 8.9 failures and the "Fail & Repair" is 10 failures (Table 5). There are 26 inverters in this simulation and unlike modules and combiners, more failures can occur when the component (inverter for this case) is repaired. This is due to the fact there are fewer inverters, so there are fewer components for the distribution to choose from. Similar behavior would then be expected for other components on the AC side, which is discussed in the following sections.

Table 5. Inverter Lightning Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al., 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
16	10[i]	10	13.2	6.8

i - The 5-year expected is assumed to be the mean of multiple realizations, though Collins et al. (2009) does not specify the confidence intervals or number of realizations.

The spread in cumulative energy production values from the "Fail Only" group is due to the failed inverters not being repaired with more energy lost than if the inverters were repaired as shown in the group of 10 realizations at the top of the graph. The difference in "Fail Only" cumulative energy production realization results is ~10M kWh over 5 years, while the "Fail & Repair" scenario is ~13,000 kWh over 5 years. The results are as expected, especially when compared to modules and DC combiners when moving to fewer parallel components such as the inverter, when the outage can have a larger energy loss impact than a DC combiner or module.

2.2.3.2 General Failure

General failure impacts to inverters (not including lightning) were modeled in SAM using data from Collins et al. (2009) as presented in Table 1. There was no effort to separate out the different events when this distribution was developed.

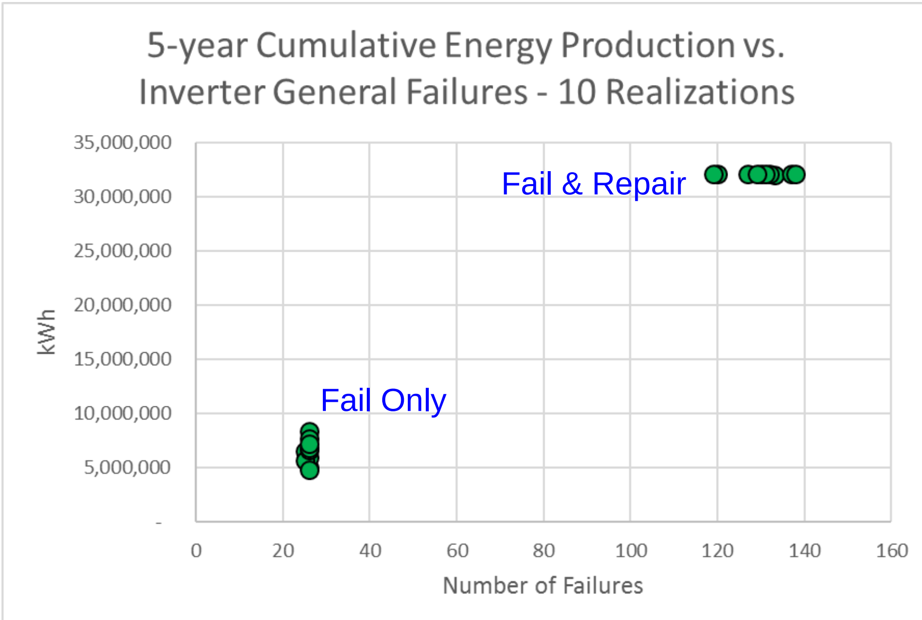

Figure 6. Simulated Inverter General Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 6 labeled "Fail Only" represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the "Fail Only" distributions is 26 failures and the "Fail & Repair" is 129.6 (Table 6). There are 26 inverters in this simulation and unlike modules and combiners, more failures can occur when the component (inverter for this case) is repaired. This is due to the fact there are fewer inverters, so there are fewer components for the distribution to choose from.

Table 6. Inverter General Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al., 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
125	132[i]	129.6	125.1	134.1

i - The 5-year expected is assumed to be the mean of multiple realizations, though Collins (2009) does not specify the confidence intervals or number of realizations.

The spread in cumulative energy production values from the "Fail Only" group is due to the failed inverters not being repaired with more energy lost than if the inverters were repaired as shown in the group of 10 realizations at the top of the graph. The difference in "Fail Only" cumulative energy production realization results is ~3.5M kWh over 5 years, while the "Fail & Repair" scenario is ~66,000 kWh over 5 years. The results are as expected, especially when compared to modules and DC combiners when moving to fewer parallel components such as the inverter, when an outage can have a larger energy loss impact than a DC combiner or module.

2.2.4 Transformer

Using the configuration outlined in Table 1, only HV transformers were allowed to fail and/or be repaired. All other failure modes were turned off. As SAM can only model an even number of transformers, the number of transformers modeled is less than the actual number, therefore the number of failures will be less than the expected value in Table 6 that we are comparing against.

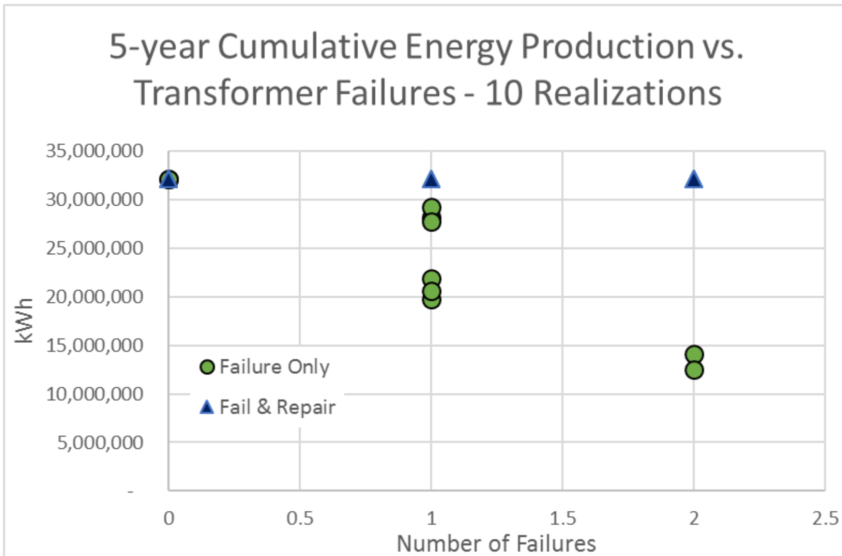

Figure 7. Simulated Transformer Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 7 that say "Fail Only" represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the "Fail Only" distributions is 1 failure and the "Fail & Repair" is 1 failure. There are 7 HV transformers inverters in this simulation where actual failures over the first five years were 5, and expected failures from the Collins et al. (2009) model were 4.

Table 7. Transformer Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al., 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
5	4[i]	1	1.5	0.1

i - The 5-year expected is assumed to be the mean of multiple realizations, though Collins (2009) does not specify the confidence intervals or number of realizations.

Due to the model limitations, conclusions on failure rate comparisons cannot be made. However, the behavior of the transformer when it is not allowed to be repaired is consistent with other components. The difference in "Fail Only" cumulative energy production realization results is ~19M kWh over 5 years, while the "Fail & Repair" scenario is ~18,000 kWh over 5 years.

2.2.5 AC Disconnect

Using the configuration outlined in Table 1, only AC disconnects were allowed to fail and/or be repaired. All other failure modes were turned off.

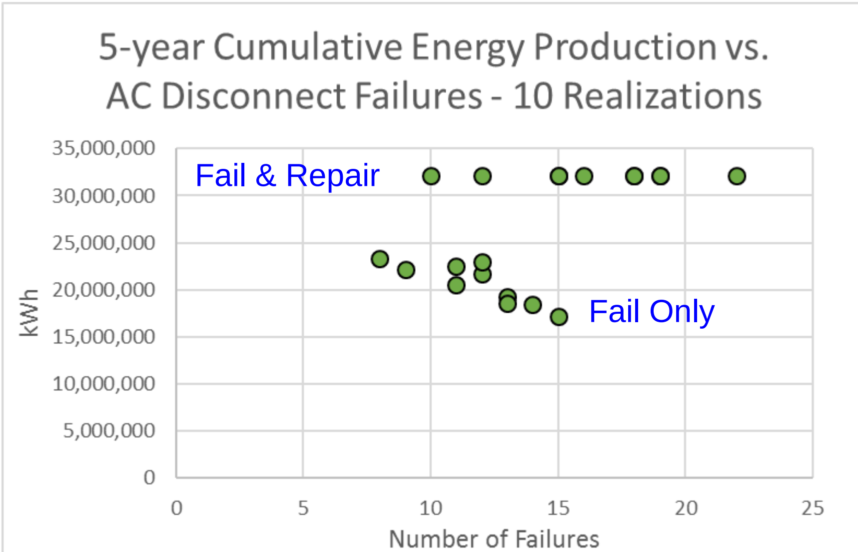

Figure 8. Simulated AC Disconnect Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 8 that say "Fail Only" represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the "Fail Only" distribution is 12 failures and the "Fail & Repair" is 16.4 (Table 8). There are 26 AC disconnects in this simulation and similar to inverters, more failures can occur when the AC disconnect is repaired.

Table 8. AC Disconnect Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al. 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
22	17[i]	16.4	19	13.8

i - The 5-year expected is assumed to be the mean of multiple realizations, though Collins et al. (2009) does not specify the confidence intervals or number of realizations.

The spread in cumulative energy production values from the "Fail Only" group are due to the failed AC disconnects not being repaired with more energy lost than if the AC disconnects were repaired as shown in the group of 10 realizations at the top of the graph. The difference in "Fail Only" cumulative energy production realization results is ~6.1M kWh over 5 years, while the "Fail & Repair" scenario is ~8,300 kWh over 5 years.

2.2.6 Grid

Using the configuration outlined in Table 1, only external grid events that prevented the PV system from exporting energy were simulated to fail and/or be repaired. All other failure modes were turned off.

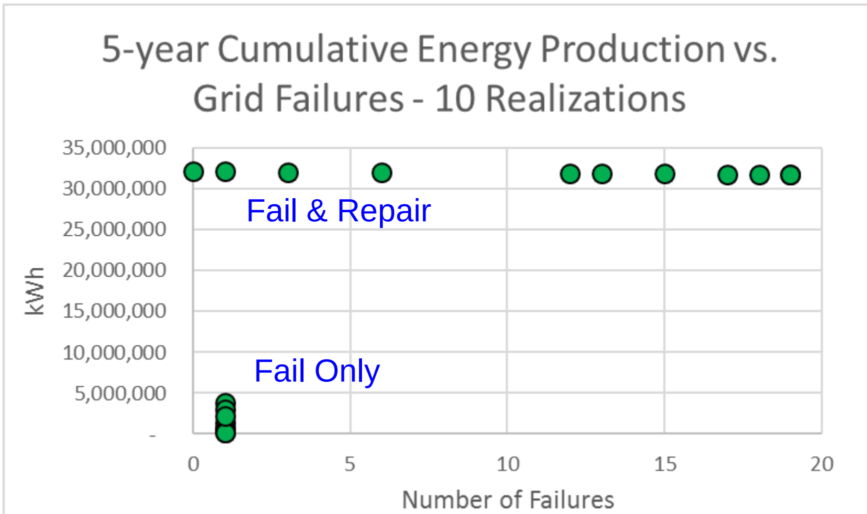

Figure 9. Simulated Grid Failures for 10 Realizations: Failure Only, Failure & Repair

The group of results in Figure 9 that say “Fail Only” represent each realization out of 10 where the failure is allowed to occur based on sampling from the Weibull distribution in Table 2. The mean of the “Fail Only” distribution is 1 failure and the “Fail & Repair” is 12.3 (Table 9). There is only one interconnection with the grid and the results in terms of energy loss differences when the grid is unavailable to accept energy from the PV plant (and not returned to service) and when the grid becomes available appear to be reasonable. The difference in “Fail Only” cumulative energy production realization results is ~32M kWh over 5 years, while the “Fail & Repair” scenario is ~352,000 kWh over 5 years. As there are no published actual or expected failure rates, a comparison cannot be made to the simulated vs. expected (Collins et al., 2009) results. The behavior of the failures and repairs based on the location of the “grid” relative to the PV system suggests that the model works correctly.

Table 9. Grid Failures – 10 Realizations for SAM Run

5-yr Actual	5-yr Expected (Collins et al., 2009)	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
N/A	N/A	12.3	17.1	7.5

2.3. Summary of Failure Only and Failure & Repair

The two figures below place all Failure Only (Figure 10) and Fail & Repair (Figure 11) plots together from Figures 3 through 9 to see relative impact between energy production and number of failures. For cases where failures occur, but are not replaced (Figure 10), the number of failures and severity based on impacts to cumulative energy production reveal that in cases where there are fewer 'redundant' components, such as grid and transformer failures, large impacts to energy production can occur. General inverter events, if not replaced, have a larger energy impact than lightning based on the frequency of events and distribution chosen to represent those events. Modules and DC combiners have less impact on cumulative energy production due to the larger number of parallel components in the system.

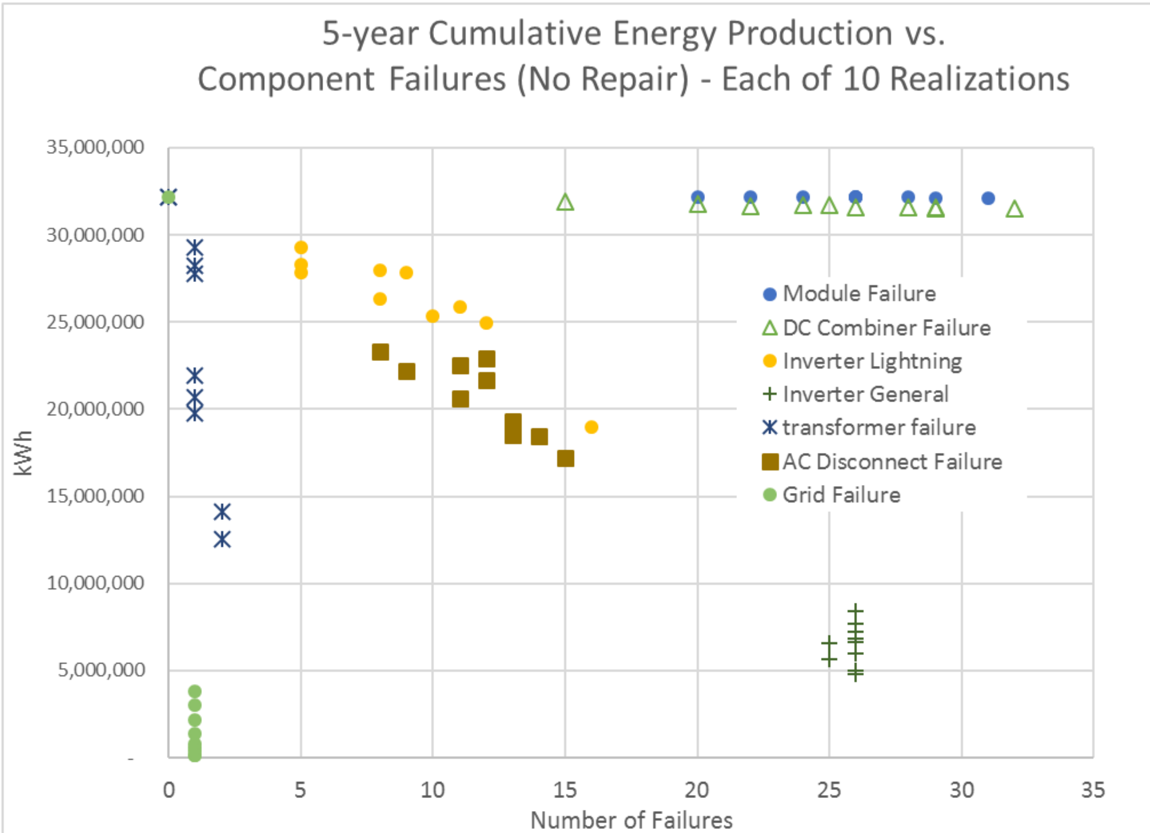

Figure 10. All Component Failure Only – Cumulative Energy Production vs. Number of Failures per Realization

In cases where failures occurred, and a repair distribution based on the best fit of the repair logs for the component is added to the model, much less energy is lost over the same 5-year time period; the behavior of some components, such as inverters, transformers and grid events is different due to fewer components on the AC side and more potential for energy loss when those components are down. For grid events, if it was never "fixed" and the PV system was not able to deliver electricity, Figure 10 shows that any event in that 5-year period may produce some energy but after the failure, no energy is produced.

For Figure 11 where grid events are considered "fixed" at some duration after the failure, the energy production spread is the largest of any component, and is a reflection of the distribution uncertainty. Because we do not have the actual number of grid events to compare against, there is no way to validate the number of events. However, we can at least see that the behavior is consistent with how an event at the main interconnection point can have on energy production with or without repairs being made to allow the PV system to export energy.

Inverters have the next largest impact with fewer failures occurring when the inverter is not repaired (with a large energy loss impact), compared to more failures that can occur when the inverter is repaired (less energy loss impact).

Transformer failures not repaired have a large energy impact based on when the failure occurs. The impact is not as large as the inverters as they failed less often, however there are fewer parallel transformers than inverters. When the transformer was repaired, the energy loss stayed within the range of other components such as AC disconnects and inverter events due to lightning.

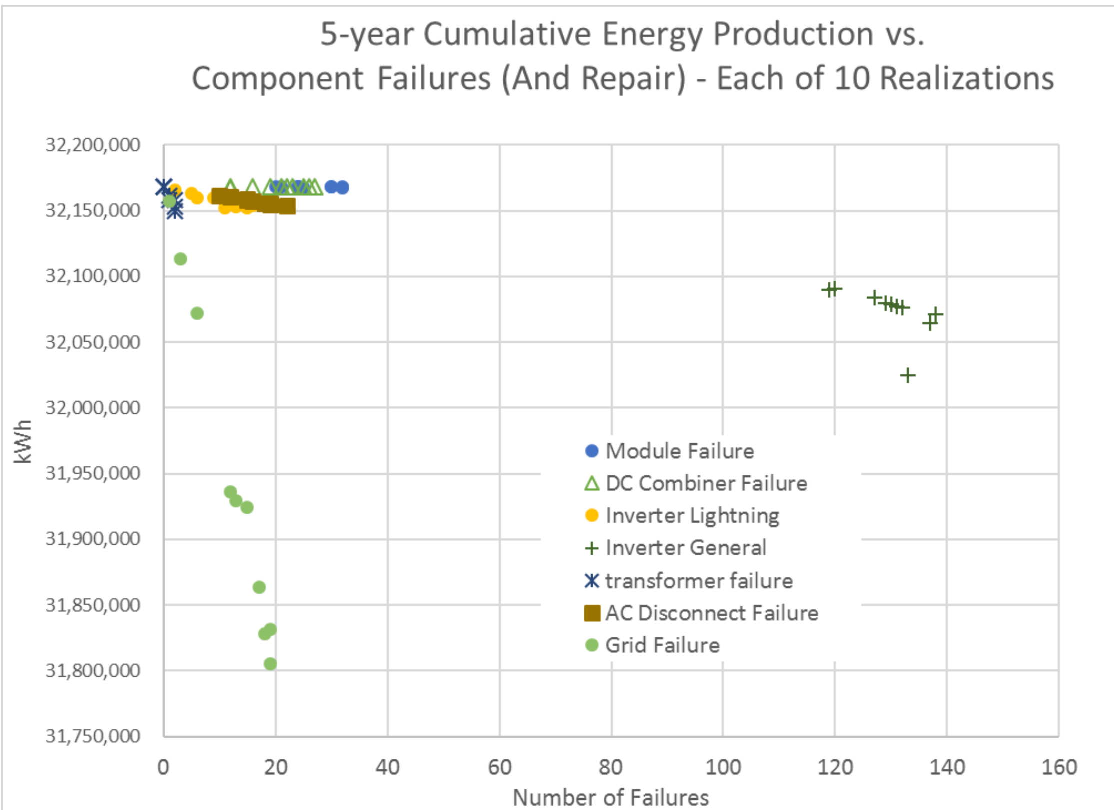

Figure 11. All Component Failure and Repair – Cumulative Energy Production vs. Number of Failures per Realization

The spread in the number of failures in the failure and repair analysis is representative of how many events were available to fit to a distribution, as well as the type of distribution developed. As these were developed by Collins et al. (2009) we do not have detailed notes on goodness of fit and other errors that may lead to a wider range in number of failures for certain components.

2.4. Evaluating Events for All Components

To evaluate all components discussed above in Sections 2.2 and 2.3, the model was run with 100 realizations and all failure modes and repair distributions were turned on to see to what degree the mean and confidence interval of 100 realizations compared to actual failures. Energy production was not evaluated in this simulation as events (faults/failures) were the only data available to compare from the Springerville system. Only general inverter events were evaluated and not the lightning events as shown above in Section 2.2.3.1. Grid results were unable to be compared to 5-year actual and expected results as they were not published by Collins et al. (2009). Results are shown both in Table 10 and Figure 12.

Table 10. All Failures – 100 Realizations for SAM Run

Component	**5-yr Actual**	5-yr Expected (Collins et al., 2009)[i]	5-yr Simulated Mean (SAM)	95% CI (upper) (SAM)	95% CI (lower) (SAM)
Module	**29**	26	26.4	27.2	25.6
DC Combiner	**34**	25	24.1	25.1	23.2
Inverter General	**125**	132	132.1	133.8	130.4
Transformer	**5**	4	1.0[ii]	1.2	0.8
AC Disconnect	**22**	17	16.9	17.8	16.0
Grid	**Unk.**	Unk.	15.6	16.7	14.5

i – The 5-year expected is assumed to be the mean of multiple realizations, though Collins et al. (2009) does not specify the confidence intervals or number of realizations.

ii – As mentioned in Table 1 footnote ii, fewer transformers than what is on-site were modeled, resulting in fewer simulated failures.

The confidence intervals from Table 10 are more tightly bound around the mean than those presented in Tables 3 through 9 above as these represent results from 100 realizations (which is the suggested minimum amount of realizations to be run if a 95% confidence interval is desired). The 5-year mean Simulated value more closely matches the 5-year Expected value (with the exception of the transformer described above in Section 2.2.4) and is not above or below the upper and lower bound of the confidence interval. The one component that had expected failures above the upper value (DC combiners with *10 realizations* as described in Section 2.2.2, Table 4) now has the Expected and Simulated failures falling in-between the confidence interval with 100 realizations. As discussed in Section 2.2.4 and Table 1 footnotes, the transformer results underestimate expected and actual failures.

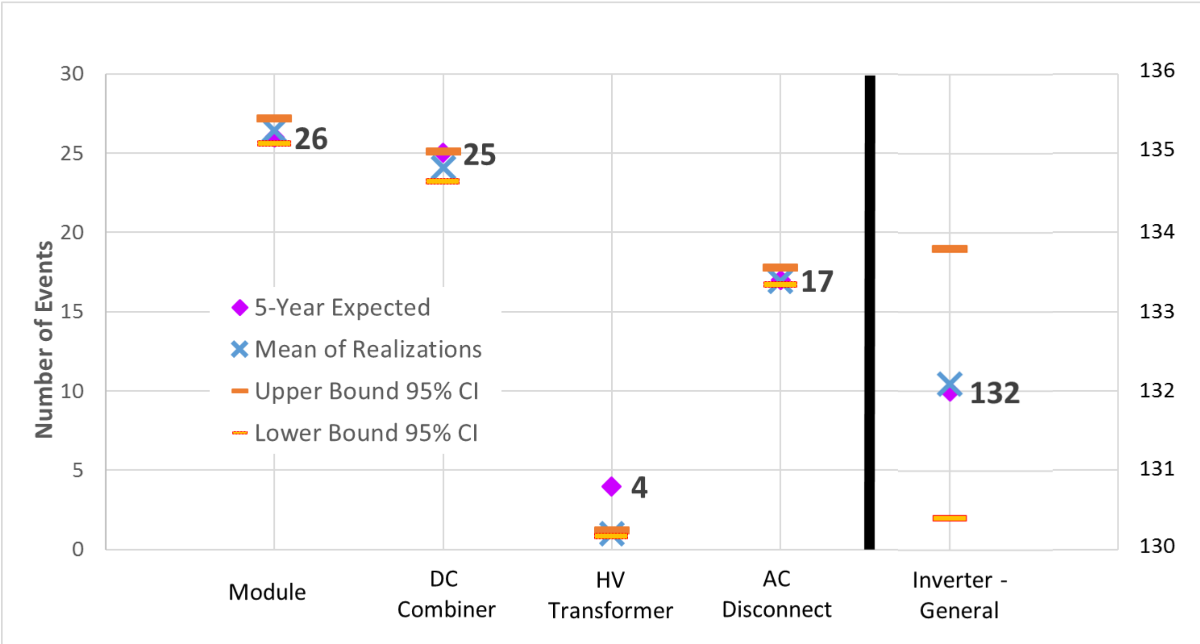

Figure 12. All Component Failure and Repair – Cumulative Energy Production vs. Number of Failures per Realization. Catastrophic Inverter Events Are Plotted on a Secondary y-axis

3. CONCLUSIONS

This paper describes the process used to compare the early proof-of-concept PV-RPM model to a new implementation of the algorithm that can be used in the System Advisor Model through the SAM LK scripting language. Simulations were run first on individual components, then all components using actual and expected failure results described by Collins et al. (2009). The behavior in terms of the number of failures and energy lost reflected the position of the component in the PV system and the number of similar or “parallel” components, indicating that the structure of code is correct when estimating energy loss from different levels of components, and failure behavior when a component is or is not allowed to be repaired.

Running the simulation with actual failure data for 100 realizations, the mean of Simulated component failure events was within the 95% confidence interval Expected events from Collins et al. (2009). The mean of the SAM Simulated failures over 5 years compared to the expected failures from Collins et al. (2009) matched well (Table 12) suggesting that the distributions from the SAM implementation of the PV-RPM model behave similarly to the proof-of-concept distributions.

It is important to note that this paper describes a PV system with data collected over a 5-year period, with close attention paid to maintenance records to develop the distributions used to estimate the failure and repair distributions. This data, if used in a different simulation, may or may not provide a similar estimate as the distributions were developed for a PV system in the 2003 to 2007 timeframe, where components and installation practices, and resulting climate may be different than a system built at any other time. The data and results, however, provide insight into how PV system and plant owners and performance modeling experts can develop fault and failure distributions to represent their own data, which can then be run through SAM using the LK scripting language to gain insight into expected failures, impacts to energy production, cost of maintenance actions and potential revenue lost as a result of that failure.

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